



Creating a multifunctional composite stator slot material system to enable high power density electric machines for electrified aircraft applications

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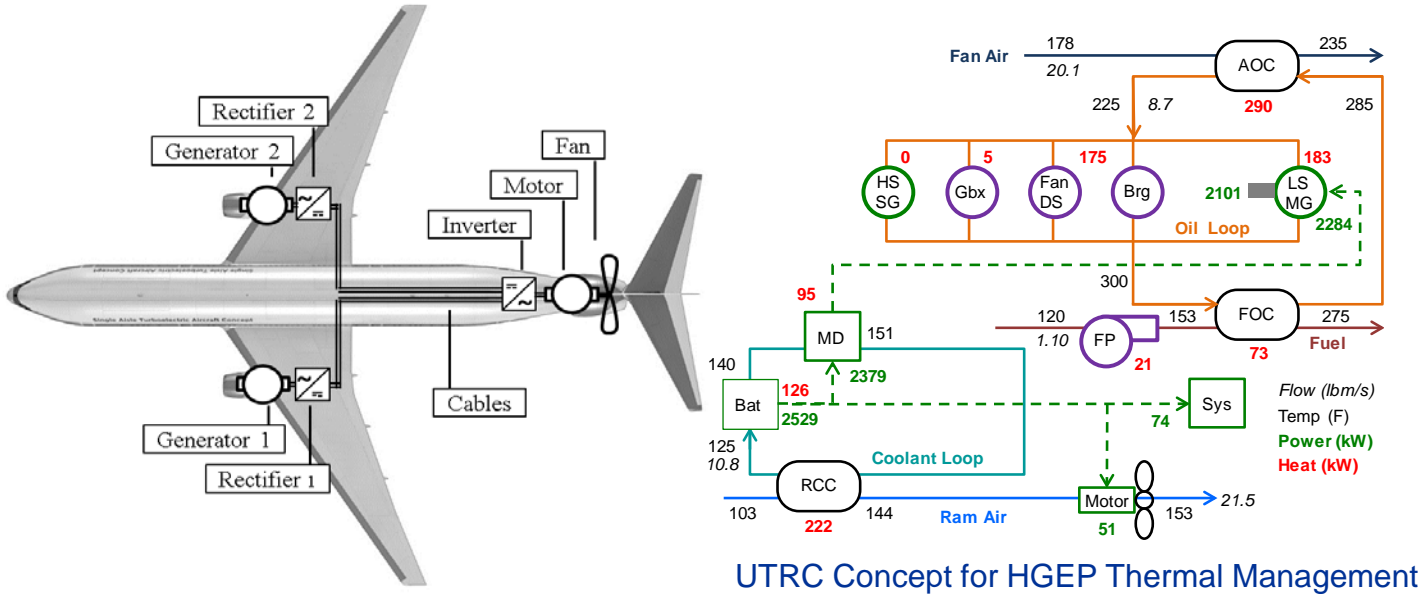
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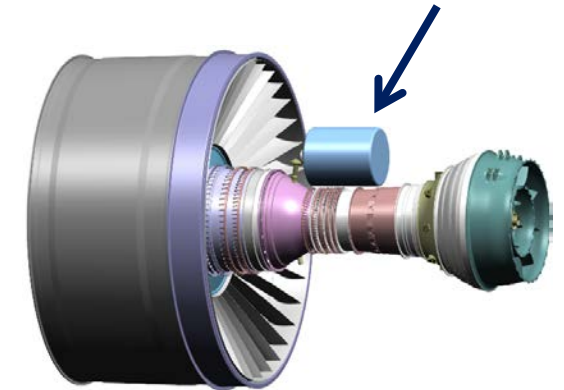
Electric Machine Motivation: STARC-ABL

Conventional tube and wing design along with minimal battery dependence makes this a near term possibility (2030ish)



Cooling Loop	Max Temp		
	°C	°F	K
Coolant	60	140	333
Oil	135	275	408

High Power Density Electric Machine



UTRC concept for Hybrid Geared Turbofan

Electrical Machines

- Two 1.4 MW generators mounted near turbines
- One 2.6 MW motor driving tail cone thruster

Geared Turbofan

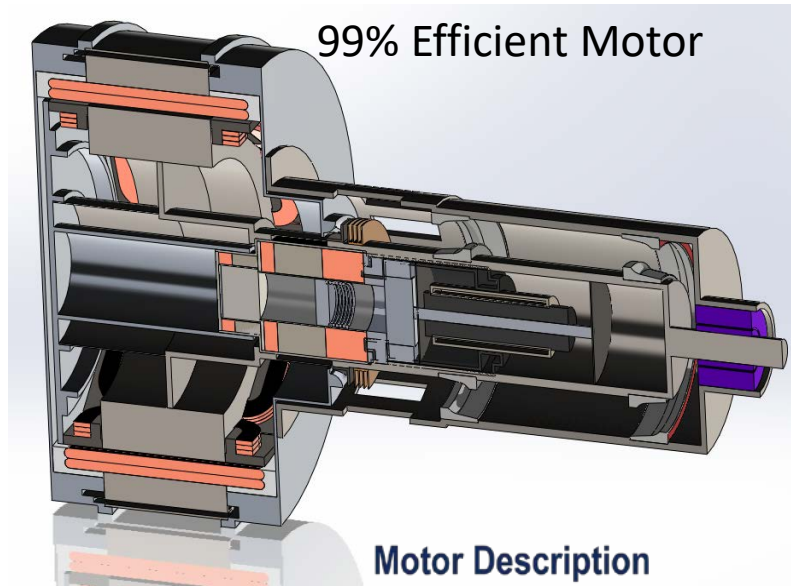
- HP Spool = ? rpm
- LP Spool = 6800 rpm (generator connects here)

Tailcone Thruster

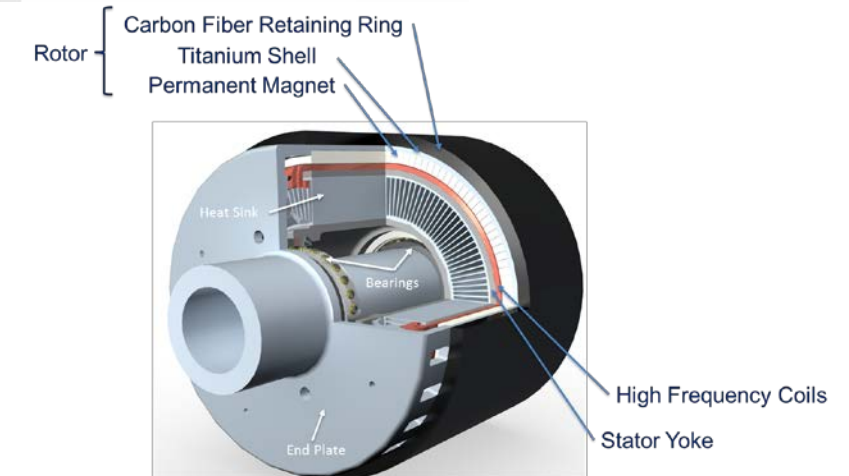
- Fan = 2514 rpm
- Diameter = 80.2"
- Hub/Tip Ratio = 0.3
- Hub Diameter = 24.1"

Electric Machine Motivation: NASA Efforts

- Internal NASA motor development
 - Target >98% Efficiency Stretch Goal 99%
 - 16 kW/kg
 - 1.46 MW
- External NASA funded motor development
 - >13 kW/kg
 - >1 MW
 - >96% Efficient
 - Teams at UIUC & OSU
- All teams have chosen Litz wire or form wound conductors to meet their goals
- High power densities = higher temperatures = more loss (10 °C increase in temperature is a 3.9% increase in resistive loss)

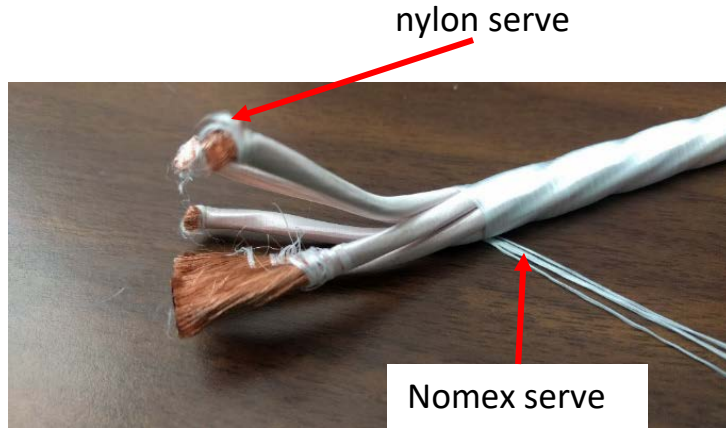


Motor Description



NASA NRA: High Power Density Motor Under Development by Professor Haran's Group, University of Illinois Urbana-Champaign. Contracting Officer Representative Andrew Provenza, NASA Glenn Research Center

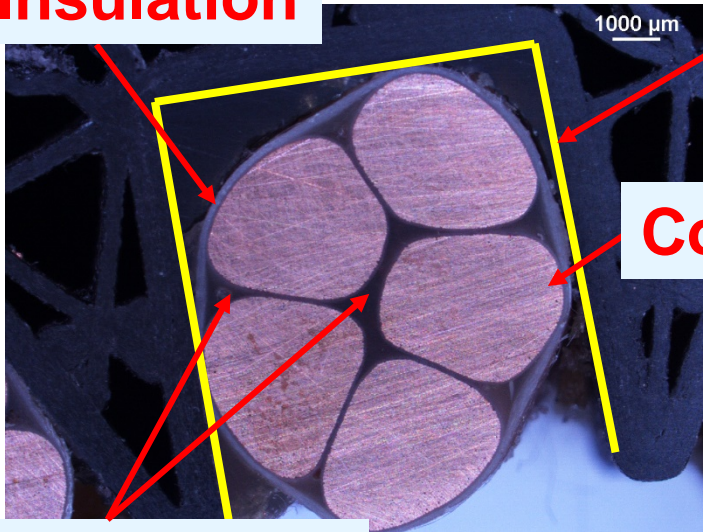
Litz Wire



- Litz wire reduces losses due to induced eddy currents
- Parallel conduction of current in the motor-strands at roughly the same potential
 - Standard magnet wire electrical insulation on each strand is a significant over design
- Litz wire offers a unique design space for new material solutions

Inside a Stator Slot

HV Insulation



Slot

Conductor

Slot

- soft magnetic material

Wire insulation

- electric isolation, polyimide ~ 0.1 W/m-K

HV Insulation

- electrical isolation, polyamide or mica (1-2W/m-K)

Potting material

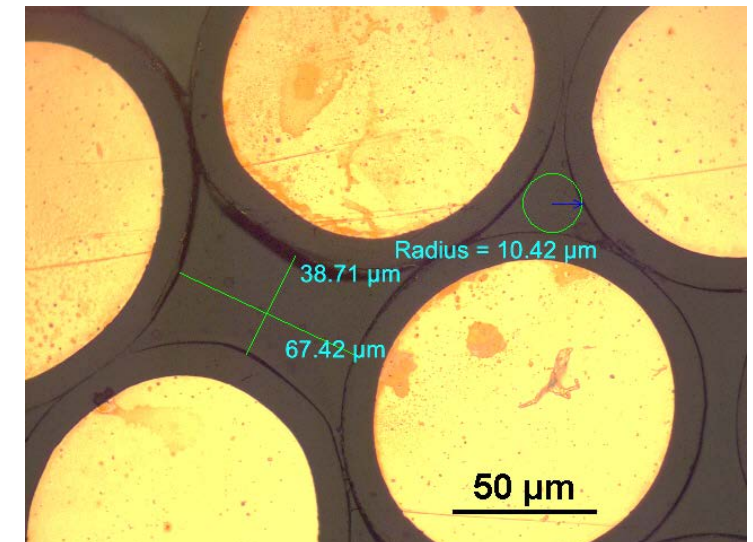
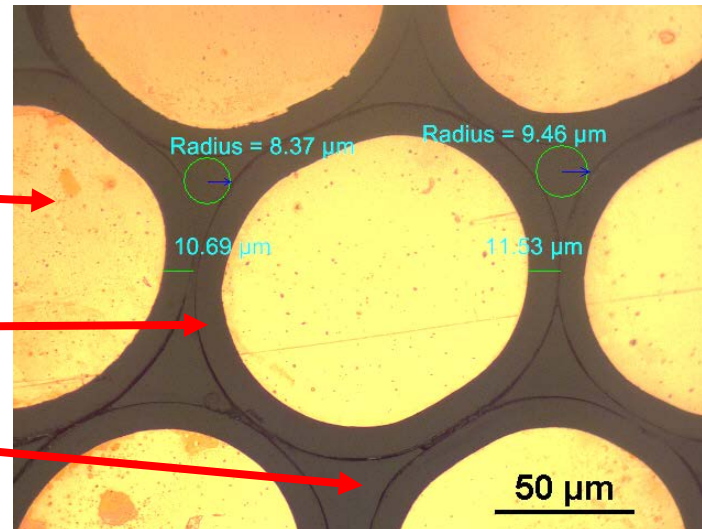
- mechanical stabilization/thermal management*
- epoxy ~ 2 W/m-K (with some exceptions)

Potting Material

conductor

wire insulation

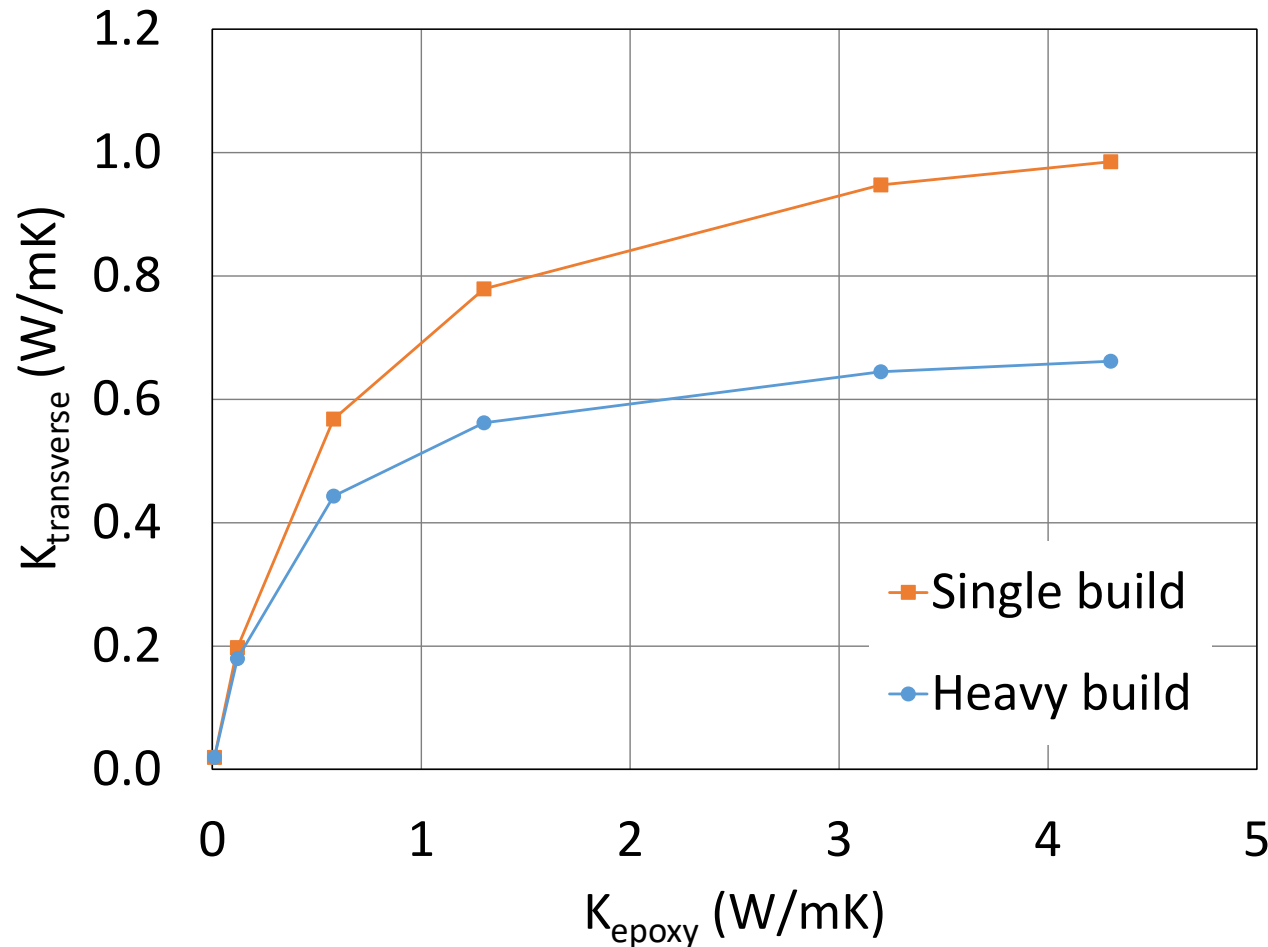
potting material



Potted AWG 38 (101 micrometer diameter) with a heavy build polyimide insulation



Thermal Effects: Potting Material vs. Wire Insulation



From the law of mixtures

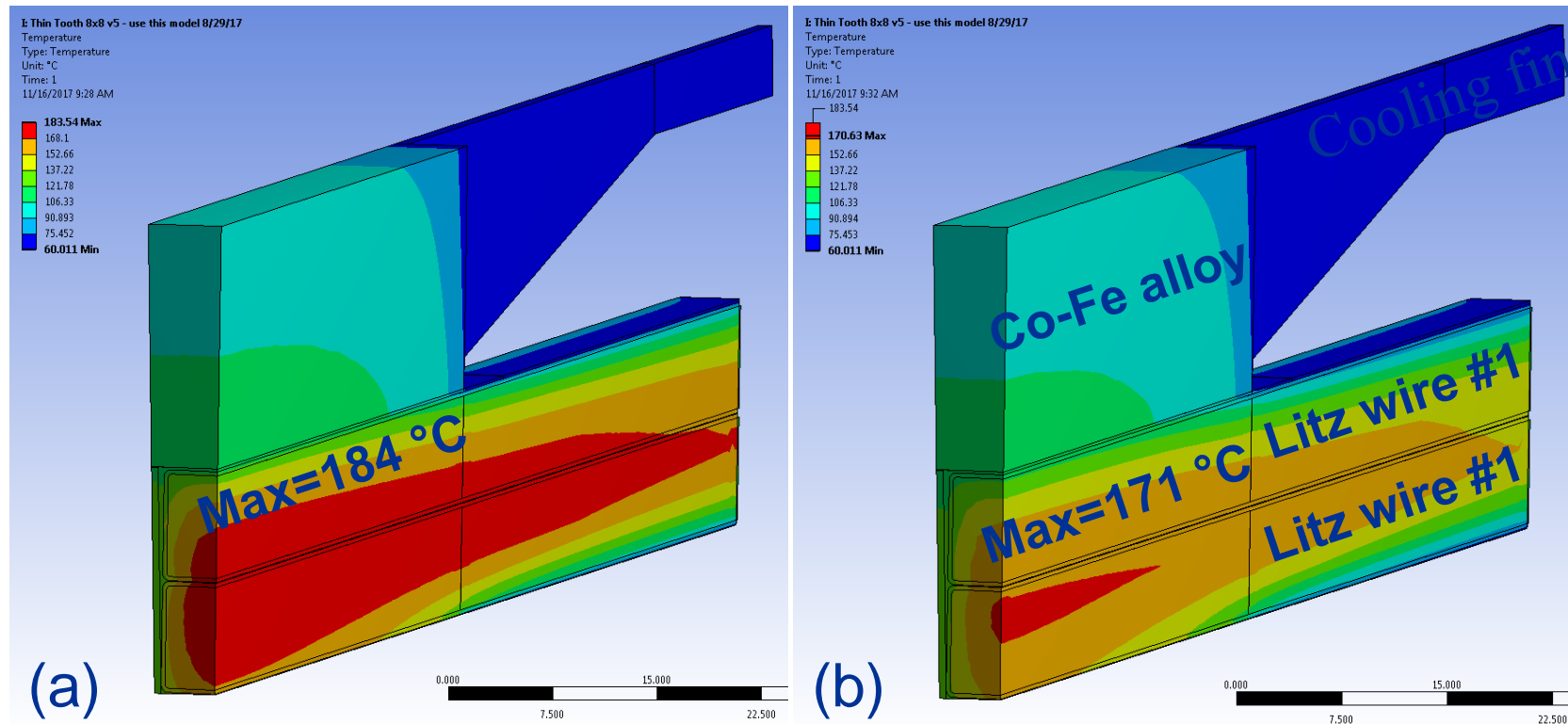
$$K_{\text{transverse}} = \frac{1}{\frac{\eta_{\text{Cu}}}{K_{\text{Cu}}} + \frac{\eta_{\text{ins}}}{K_{\text{ins}}} + \frac{\eta_{\text{epoxy}}}{K_{\text{epoxy}}}}$$

$$K_{\text{axial}} = K_{\text{Cu}}\eta_{\text{Cu}} + K_{\text{ins}}\eta_{\text{ins}} + K_{\text{epoxy}}\eta_{\text{epoxy}}$$

- Increasing the thermal conductivity of the potting material (epoxy) has a significant effect on thermal conductivity
- Wire insulation is a significant thermal choke
- Does ins the traditional wire insulation necessary with Litz wire-could it be replaced with the potting material

Finite Element Analysis (FEA) of the High Voltage Insulation

High voltage insulation breakdown ($> 2\times$ operating voltage of the motor) is necessary between phases in a stator slot and between the conductor and back iron

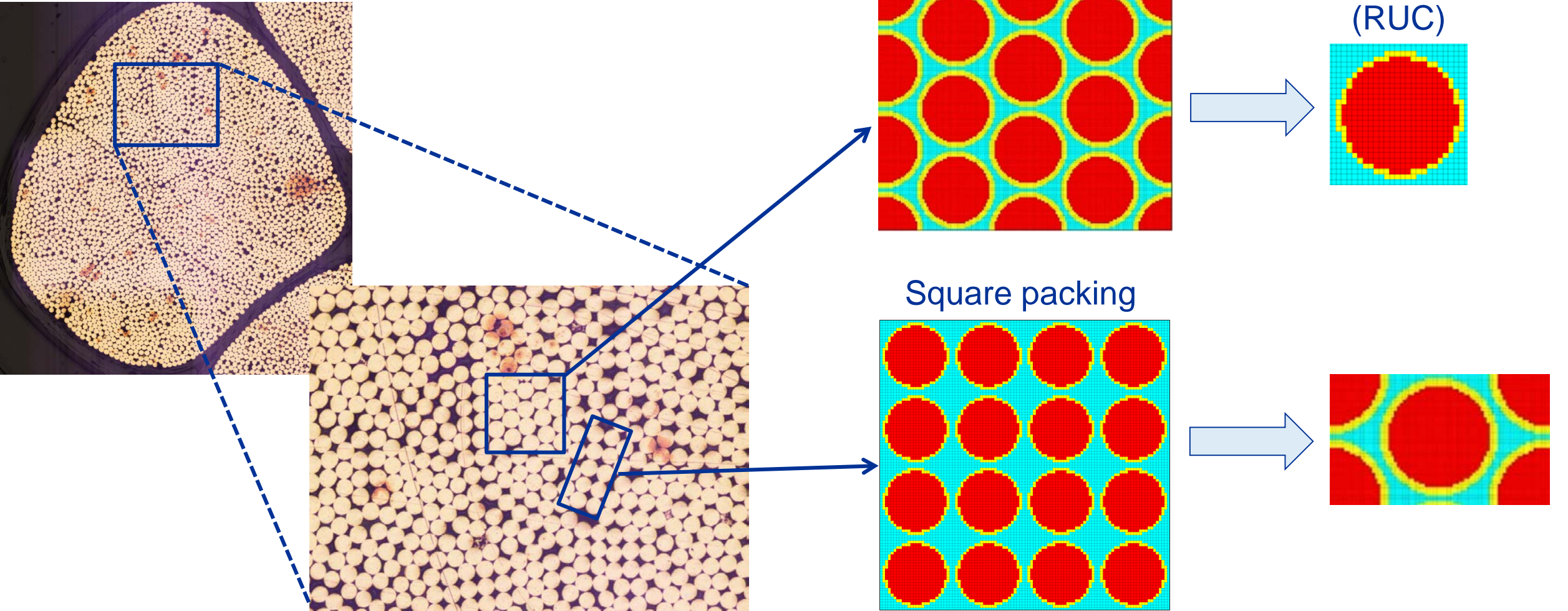


FEA of a theoretical motor slot. High voltage insulation wraps each Litz wire. High voltage insulation thermal conductivity (a) 0.12 W/m-K and (b) 0.24 W/m-K



Rudimentary Unit Cells (RUC)

RUCs allow for rapid reproduction of common (repeated) structures in a composite material

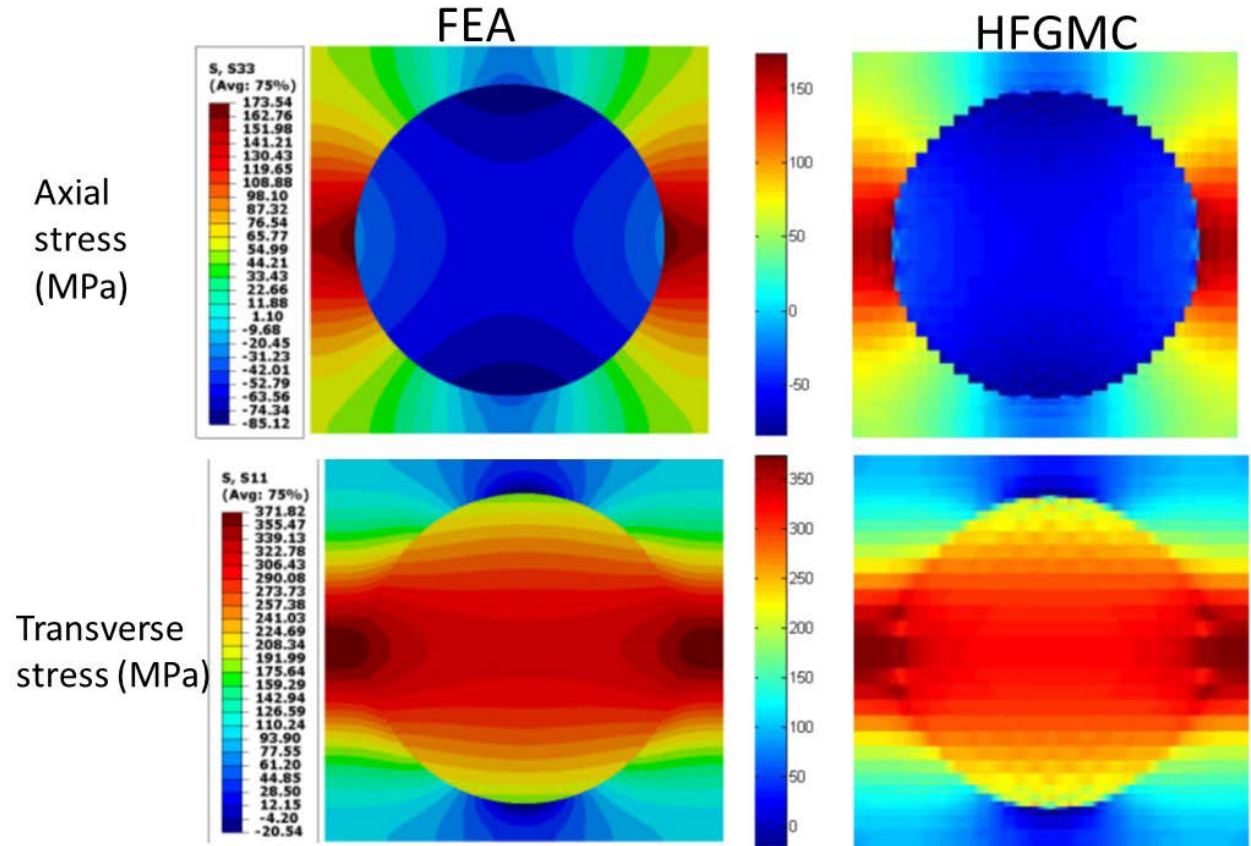




High Fidelity Generalized Method of Cells (HFGMC)

Provides a 10x increase in computational speed while minting most of the accuracy of FEA

Makes computations of large number of the repeated structures possible



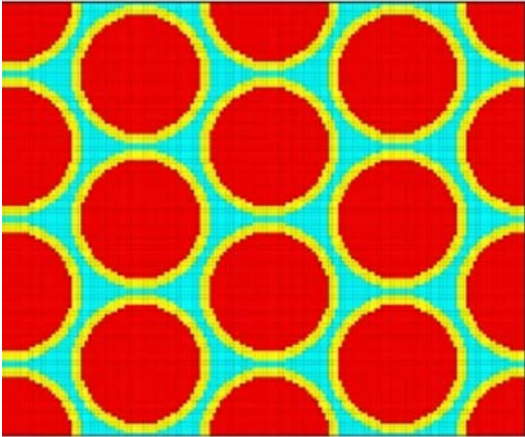
Preliminary Micro Thermal Modeling Results

Hexagonal

Conductor ~ 55-60%

Insulator ~20%-30%

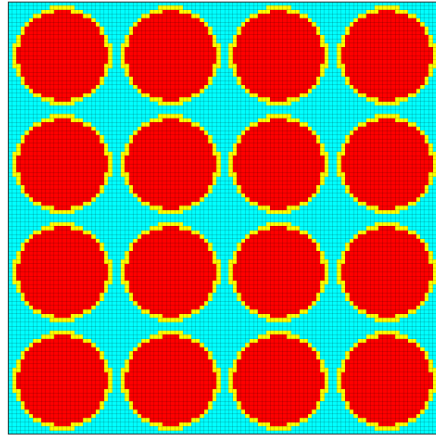
Potting material~15-20%



$$\begin{aligned}K_{\parallel} &= 380 \text{ W/m-K} \\K_{\perp 22} &= 0.79750 \text{ W/m-K} \\K_{\perp 33} &= 0.79529 \text{ W/m-K}\end{aligned}$$

Square

<<Place holder for
pickling factors>>



Square

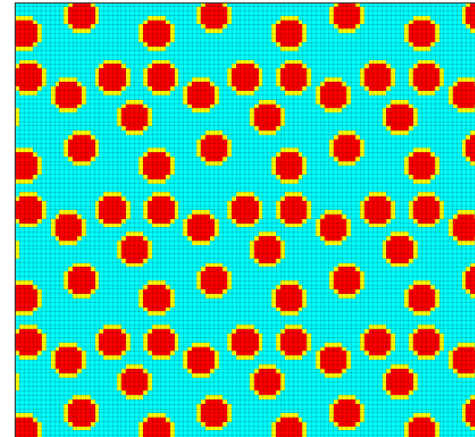
$$\begin{aligned}K_{\parallel} &= 290 \text{ W/m-K} \\K_{\perp 22} &= 0.86730 \text{ W/m-K} \\K_{\perp 33} &= 0.86730 \text{ W/m-K}\end{aligned}$$

Random I and II

Conductor: 45-50%

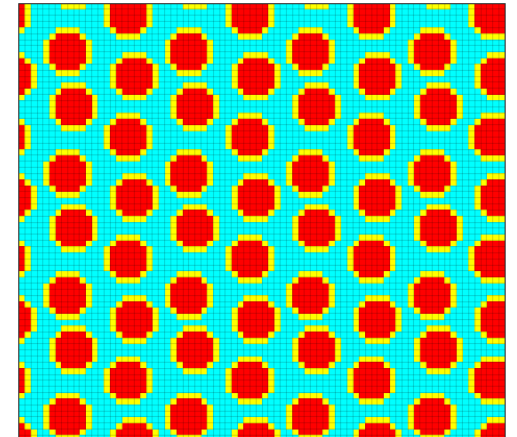
Insulator: 20%-30%

Potting material: 25-30%



Random-I

$$\begin{aligned}K_{\parallel} &= 240 \text{ W/m-K} \\K_{\perp 22} &= 0.442 \text{ W/m-K} \\K_{\perp 33} &= 0.421 \text{ W/m-K}\end{aligned}$$



Random-II

$$\begin{aligned}K_{\parallel} &= 255 \text{ W/m-K} \\K_{\perp 22} &= 0.528 \text{ W/m-K} \\K_{\perp 33} &= 0.524 \text{ W/m-K}\end{aligned}$$



Summary & Conclusions

- Conceptualizing the insulation materials systems as composite is the key gaining to multi-functionality
 - Electrical
 - Thermal
 - Mechanical
- Composite approach provides modest, achievable goals can be set. thermal conductivities for
 - potting materials $> 1 \text{ W/m-K}$, and
 - High Voltage Insulation $\sim 0.5 \text{ W-m/K}$
 - possibly replacing or eliminating the insulation material on the Litz wire. These
 - goals are backed up by finite element modeling.
- Higher fidelity micro thermal modeling along with testing and model validation will bring more clarity to how the physical system behaves and will also refine the material development goals.



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Electric Machine Insulation Development Team

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- Marisabel Kelly
- Kathy Chuang

99% Efficient Motor Development Team

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- Pete Kascak
- Justin Scheidler
- Ryan Edwards
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- Jarred Wilhite



Thank you!